WG 1.2 report: Stars, Planets and the Milky Way

Sarah Martell (WG lead), Joanne Dawson, Amanda Karakas, Ben Montet, Melissa Ness (topical leads), Chelsea Huang, George Zhou et al. (contributed papers on exoplanet studies)

Executive summary

This Working Group focused on five main topics: exoplanets, theoretical astrophysics, radio/submm observations, optical/IR observations, and survey science. Community consultation meetings were widely advertised and held via videoconference. These meetings were used to discuss progress against the previous Decadal Plan, major science themes for the next decade, key opportunities and challenges, and enabling strategies and resources. In addition to the planned science topics, the conversations also touched on the Australian Space Agency, high-performance computing resources, ESO membership, instrumentation development, career pathways, and ARC funding. Through our discussions, a number of themes have become apparent, which we elaborate on in this paper.

Key research questions

The research questions we expect to have the highest profile in the next decade are

- How do planetary systems, including Solar System analogues, form and evolve?
- What are the factors that determine planetary habitability, and how can we best detect biosignatures and technosignatures in the Universe?
- Where in the Universe are elements forged, and how are they transported into new environments and new generations of stars?
- How can we use detailed studies of gas, stars, and dark matter in the Milky Way and the Local Group to investigate the physical processes driving galaxy evolution?
- How can we best leverage large data sets and advanced analysis methods to understand the properties and evolution of stars, planets, and the Milky Way?

Recommendations

The key actions and choices needed to optimise Australia's research outcomes in the next decade in the area of Stars, Planets, and the Milky Way are

- Maintaining the 2024 level of access to/participation in 4m-class, 8m-class and ELT-class ground-based optical/NIR telescopes
- Working toward full SKA operations, with an appropriate complement from SKA Pathfinder facilities and other radio telescopes
- Enabling active participation by a broad segment of the research community in large-scale international collaborations
- Expanding the computational services available to the community, including data archiving, sharing, processing, and HPC
- Supporting the development and distribution of novel analysis methods and code resources
- Improving career paths for key nonacademic roles in computation and engineering
- Creating an effective national-scale infrastructure for collaboration
- Building instrumentation for a major ESA or NASA space mission

Theme A: Australian research leadership in the next decade
The next decade will bring major advances in the Australian community in the research area of Stars, Planets and the Milky Way, thanks to new telescope facilities, instrumentation, analysis methods, and collaborations. The continuing development of the Australian space industry will create new opportunities for cubesat launches, technology development, and career paths. Here we give brief descriptions of the research areas in which Australia can and should lead over the next decade.

Habitable worlds: Earth and its relatives

Exoplanet researchers are uncovering the fundamentals of planetary formation and evolution processes using large samples of exoplanets delivered by transit- and radial velocity-based surveys across a wide range of compositions, orbits, and host stars. This is supported by detailed observations and modelling across Solar System bodies, protoplanetary disks, planetary atmospheres, stellar activity, and star-planet interactions. The field of planetary habitability is rich and complex, connecting strands from planet formation, atmospheric physics, stellar activity, and astrobiology.

Australia's complementary access to radio/sub-mm and optical/IR facilities provides a unique opportunity for international leadership in these fields through a multi-wavelength coordinated approach to stellar activity and the interactions between stars and their planets. The founding of the Australian Space Agency in 2018 and the continued development of space-related industry in Australia are creating possibilities for Australian astronomers to develop new instrumentation for space missions. A future mission, perhaps as a partnership between the Australian Space Agency and international partners, would provide an opportunity to develop new connections between industry partners and researchers and to draw on our strength in space-based exoplanet observations.

Stellar modelling and stellar physics

Stellar physics is a major connection point between optical and radio, observations and simulations, and multiple rungs of the cosmological distance ladder. The impact of this field has been recognised in recent years with good success rates in ARC fellowships and grant funding. Stars are the "subgrid" for much of our understanding of galaxies, and it is essential that we thoroughly understand the details of element formation in stars and supernovae, and the effects of stellar mergers and binarity on stellar populations, in order to correctly interpret the properties of those larger systems.

Stellar physics also crosses methodological lines. Asteroseismology provides a unique view into stellar interiors, and uses machine learning together with traditional time-domain data analysis methods. Stellar rotational and magnetic evolution is a major topic for Solar mass and low mass stars, including the effect these stellar phenomena have on planets and their atmospheres. Both optical (eg, TESS) and radio observations are key to tracking and understanding them. In the radio, activity can be identified by ASKAP through wide-field transient searches at an appropriately high cadence, and followed up with high time resolution dynamic spectra, including polarisation, at lower frequencies with ATCA.

Life cycle of the Milky Way

As the galaxy where we can collect the most detailed observations, the Milky Way is a unique laboratory for studying galactic structure and evolution on many different spatial scales. Milky Way studies also provide a major opportunity to tie together multiple wavelengths and messengers, approaches and specialty areas. These include ISM composition and enrichment, stellar feedback, stellar and gas dynamics, galaxy accretion, dark matter, and astroparticle physics.

Truly using the Milky Way as our closest laboratory for understanding the key physical processes we observe throughout the Universe means moving beyond exceptionalism, and placing the Milky Way as a galaxy that is part of an interacting system of galaxies, a site of star formation, gas outflow and infall, and using it to investigate the role of magnetism, plasma and high-energy processes in a galaxy's structure and star formation cycle. Australia has world-class expertise in Milky Way and local system ISM and magnetism, centred around the groups leading the POSSUM and GASKAP surveys, and we are well placed to take a leading role in magnetism projects within the SKA. We are also strong in ISM evolution on the path to star formation from both the theoretical and observational perspectives, and a concentration of world-leading expertise in Galactic HI.

Australia has been at the forefront of using VLBI to map out Galactic structure in the Southern sky, targeting masers in star-forming regions. Present-day Milky Way structure and a dynamic sense of Galactic evolution will also come from projects like LSST, 4MOST and SDSS V, combined with future Gaia data releases, which will deliver information on the ages, orbits and compositions of large numbers of individual stars. Developing methods for comparing these large and multidimensional data sets against simulations of galaxy evolution, and against observations of Milky Way analogue galaxies, will be a major undertaking that Australia is well placed to lead over the next decade.

High-detail observations

Focused, high-precision studies are an essential complement to large survey projects, providing a "reality check" anchor point and connecting the observed large-scale trends to the underlying physics. Machine learning and other rapid classification methods can identify outliers in large data sets, for example extremely metal-poor stars in GALAH or rare supernovae in LSST, but understanding their properties and origins and placing them correctly in the larger model requires specific attention.

Extragalactic archaeology

The horizon for Galactic archaeology is expanding to include the entire Local Group, with comprehensive moderate-resolution (R~20,000) spectroscopic observations of the Milky Way's dwarf satellites to be taken by the 4MOST and WEAVE large survey programs, whose science operations are starting imminently. Large low-resolution (R~4000) samples of stars in Local Group dwarf galaxies and M31 are planned for the ongoing SDSS-V Local Volume Mapper survey and the potential future WST and MSE programs.

This outward step in star-by-star observations is mirrored by an increase in spatial resolution and sample size for IFU studies of external galaxies in projects like Hector, SAMI, and GECKOS. Together these new research directions present a major opportunity for the Galactic and extragalactic research communities to collaborate on bridges across the methodological divide.

Smaller communities with big impact

Larger research fields and collaborations are not the only ones doing high-impact work in Australia. In the very nearby Universe, Australians play leading roles in Solar physics, space weather, and asteroid detection and characterisation. Small-diameter multi-telescope facilities like Minerva and SONG provide a unique capability in time-series monitoring for in-depth studies of exoplanets and stellar physics. Understanding the merger events detected at cosmological distances by gravitational wave observatories requires careful study of star forming regions and massive stars in the Local Group. Smaller research fields are an opportunity for Australian researchers to lead on the international stage.

Theme B: Observing facilities are a critical resource
Fundamentally, astronomical research requires the ability to collect and analyse new data. The results of observational studies always point to future work that will confirm the result in a different population or environment, or extend the analysis to a new wavelength regime or a higher level of detail. Theoretical and computational studies aim to predict, replicate and explain the real Universe, and therefore must have observations to compare to.

For the next decade, it is critical that we ensure access to world-class facilities across the electromagnetic and multimessenger spectrum. The observational work being done in the research community will necessarily be shaped by the facilities that are available. Much of the Australian optical community's current observational work is built around the capabilities of the Anglo-Australian Telescope, and Australian astronomers have been highly successful at winning time, both in Large Programmes and individual PI projects, with the European Southern Observatory's telescope facilities. Radio and submm studies in the area of Stars, Planets and the Milky Way leverage MWA and the ASKAP telescopes along with ATCA and Parkes. The success of our community's research agenda over the next decade requires these, or equivalent, facilities.

Major facilities: ESO and SKA

SKA is a massive international project with its own momentum, and Australia has an important role as the host for the SKA-Low antennas, which are expected to finish construction by 2028. SKA will create new opportunities for stellar and Galactic science, purely at radio frequencies and in combination with optical studies. With the start of SKA operations coming in the next decade, it is strategic to prioritise the research that will use SKA-mid and SKA-low capabilities. Experience with the SKA precursor facilities has built a good foundation, and Australian PIs have been quite successful in securing MeerKAT time.

VLT access can dominate the conversation when discussing full Australian membership in ESO; however, ALMA, E-ELT, and smaller optical telescopes including VISTA, VST, and NTT are all very well aligned with the science goals of WG 1.2. The current and upcoming instrumentation on the VLT has ideal capabilities for research in Stars, Planets, and the Milky Way, including high angular resolution imaging with SPHERE and GRAVITY, high-resolution spectroscopy with ESPRESSO, FLAMES and UVES, and low- to medium-resolution spectroscopy with FORS2, X-Shooter and MUSE. The Australian-led MAVIS instrument currently being built for the VLT will grant new access to imaging and spectroscopy in dense fields thanks to AO corrections.

Australian astronomers have made excellent use of ALMA to date to study planet formation, astrochemistry, and evolved stars. Full ESO membership would provide more consistent ALMA access, which would benefit the researchers who have already built expertise at these frequencies, and would also incentivise further development of this skillset in the Australian community.

Current facilities: radio
The ASKAP surveys will continue to run over much of the lifetime of the next decadal plan. With a continued expansion of radio capabilities in ASKAP and MWA, we anticipate important progress in the next decade in research fields including Galactic gas cycling, star-planet interactions, and supernovae and other stellar transients. ASKAP and MWA will both continue to be relevant in transient searches because they are wide FoV, image-plane transient surveys.

Continued upgrades of the older Parkes and ATCA facilities are keeping those observatories relevant, but there is risk that these could be seen as less of a priority and potentially shuttered with the rise of SKA. This loss would put Australian astronomers at a significant disadvantage scientifically; major survey facilities will always need followup and complementary work on smaller instruments. For example, ATCA is an outstanding instrument for radio stars and star/planet interactions, and for Galactic transients in general, ATCA is the main follow-up machine – and is capable of observing frequencies that SKA-mid will not achieve. With the current BIGCAT upgrade, its capabilities will only improve, and this improvement should be leveraged over the next decade. Parkes is planning an upgrade at high frequencies to the "UWH" receiver, which will add capability in many of the science cases in WG 1.2, including stellar variability, star formation, and VLBI.

Current facilities: optical
The Anglo-Australian Telescope remains a critical resource for the members of WG1.2, and its continued operations must be guaranteed beyond the end of the current funding agreement in 2025. Moving the Australian Astronomical Observatory from Federal government funding to the University sector in 2018 has not proved to be a positive change for observational astronomers. The previous funding level for Anglo-Australian Telescope operations was quite lean, and it has not been possible to secure the same amount of funding from a loose alliance of university research offices and vice-chancellors, even with a significant level of guaranteed observing time in exchange for funding. This was then compounded by the effects of the COVID-19 pandemic on university budgets. Since the transition AAT has lost many experienced engineering staff, and has been unable to recover quickly from hardware faults in the more complex instruments. This has had major impacts on data acquisition for survey programmes, and on time sold to external users.

The closure of the MOPRA telescope in 2014 is an illustration of the potential consequences from the loss of a unique telescope facility. Although observational studies of star formation using Galactic masers were a significant component of the previous decadal plan, the number of such publications led by Australian researchers dropped by 73% from the 2006-2015 decade to the 2016-2024 decade[1]. Many of the researchers involved in the earlier, highly active phase of this work have changed research fields, left Australia, or left astronomical research careers altogether. Within WG1.2 there is concern that researchers focusing on exoplanet characterization, stellar physics, and Galactic archaeology could be similarly forced to change their research focus or their career trajectory without access to the AAT.

---

[1] Our specific ADS query was abs:"maser" abs:"star formation" year:2006-2024 AND (aff:"Australian Telescope National Facility" OR aff: "International Center for Radio Astronomy Research" OR aff:"adelaide" OR aff:"james cook" OR aff:"macquarie" OR aff:"tasmania" OR aff:"new south wales" OR aff:"western australia" OR aff:"sydney" OR aff:"csiro") with filters for ONLY astronomy, ONLY refereed, EXCLUDE PhD thesis, then we filtered the list for first authors with affiliations at the institutions in the query, and removed extragalactic studies.

Future facilities: optical

The start of observations for SDSS V, LSST and 4MOST will enable larger and more complex studies in Galactic archaeology and stellar physics for those Australian researchers with data access rights. Both WST and MSE are conducting science planning exercises for massively multiplexed spectroscopic surveys that will include comprehensive samples of stars across the Local Group.

30m-class telescopes have been slower in moving from concept to reality than originally projected due to limitations on both funding and access to culturally significant mountaintop sites. However, some of them will start to become operational in the span of this Decadal Plan. The European Extremely Large Telescope is aiming to start science verification in 2028, and the Giant Magellan Telescope is planning for first light around 2030. Australia is a long-time member of the GMT consortium, and we will be ready to take advantage of its unique instrumentation when it comes online. Australian involvement with GMT includes the design and construction of the GMTIFS spectrograph, the development of the MANIFEST fibre positioner and the Laser Tomography adaptive optics system, and the development of instrument specifications and science requirements for the G-CLEF and GMACS spectrographs. If Australia was to become a full ESO member, that would create additional opportunities for our researchers to lead or contribute to instrument design and construction for the E-ELT.

Major international collaborations

In 2024 Australia formally secured data rights in the Vera C Rubin Observatory Legacy Survey of Space and Time for 47 Principal Investigators plus 188 Junior Associates, putting us in a position where the vast majority of WG 1.2 members who want to use LSST data will be able to. We anticipate high-impact research in areas including stellar variability, novae and supernovae, Galactic structure, and the merger history of the Milky Way to flow from our involvement with LSST.

Both SDSS V and 4MOST are major international projects with some Australian participation that will begin collecting data imminently. Australia has a small number of individual members in SDSS V whose role has grown in recent years, with significant leadership in the data analysis pipeline for the Milky Way Mapper project coming from Monash University. In the case of 4MOST, the University of Western Australia and Macquarie University are institutional members, the WAVES and 4HS surveys are led from Australia, and there are a small number of other individual members in Australia.

Both projects are set to deliver massive spectroscopic (optical/infrared) data sets with relevance to Stars, Planets and the Milky Way. The membership of WG 1.2 would benefit from expanded access to these projects in the Australian community, perhaps through a national participation group. Broader access to SDSS V and 4MOST would allow access to proprietary data, and would enable Australian astronomers to build collaborative relationships within those teams.

Space facilities

WG 1.2 has as an aspirational goal that Australian astronomy should engage seriously with the Australian space industry, building expertise and connections leading to the ability to design and build instrumentation for a future exoplanets-related space mission like the NASA Habitable Worlds Observatory.

Space telescopes have become more central to WG 1.2's science focus over the past decade. The Gaia and TESS missions (ongoing) and Kepler/K2 mission (completed) have brought a wealth of data on exoplanets, Galactic kinematics, stellar variability, and asteroseismology, and the upcoming PLATO mission will extend the search for habitable zone planets to the Earth-sized regime. JWST has quickly had a major impact on exoplanet studies since its start of operations by providing a new and complementary wavelength range. The upcoming Euclid and Roman missions, both due to be launched around 2026, will provide wide-field, deep-drilling, and time-series data with applications across all of the WG1.2 science areas.

Theme C: Computational resources are essential
The astronomical research community in Australia has put significant effort and funding into broadly useful computational resources such as OzStar, Data Central, ADACS, and the Pawsey Supercomputing Research Centre. These resources must expand to meet the increasing data volumes and increasing sophistication of data processing and analysis methods. Over the next decade, specialised archives and resources like the Australian SKA Regional Centre (AusSRC) and the LSST Independent Data Access Center (IDAC) will come into operation to support those mega-scale observing projects.

Research in the area of Stars, Planets and the Milky Way will be most successful with an overall master plan for observational data and associated computational services that can meet community needs for fast, reliable data access and data analysis capabilities, ensure adherence to IVOA standards and FAIR research principles, and leverage large-scale resources like the National Computational Infrastructure and the Australian Research Data Commons.

High performance computing

Australia has distinct strengths in theoretical and computational astrophysics. We have expertise in modelling star and planet formation, stellar evolution and nucleosynthesis, core collapse supernovae, tidal disruption events, and black hole formation. Our theoretical community has a close relationship with the observational community, enabling a cooperative and productive research cycle.

One challenge for this community is that a gap in observational facilities limits our ability to grow into new theoretical spaces. As an example, it does not make sense to try to build capabilities in theoretical astrochemistry without also having direct access to ALMA observations.

Computational research by its nature is always pushing the available technology to its limits, whether that is in simulation size, resolution, dimensionality or fidelity. We do not currently have access to allocations of HPC time large enough for the major "flagship" simulations that our researchers are capable of building. This gap between the available and desired resourcing was also noted in the previous Decadal Plan, and has not been closed. This situation presents a significant limitation on Australia's ability to lead in the theoretical research space on an international stage.

Data driven astronomy

Novel data analysis methods that can process and analyse large data sets in an automated way are important for the current generation of large observational survey projects like GALAH, GLEAM and VAST, and they will be an absolute requirement for much larger upcoming projects like 4MOST, LSST and SKA. As an example, in LSST observations of tidal disruption events will go from a few tens of events to a few thousands, and we will need to make a significant investment in both theory and software tools to interpret and understand such a major boom in data.

Australian astronomers have significant theoretical expertise in modelling stars' formation, evolution, death, and nucleosynthesis. We boast world-leading expertise in modelling stellar atmospheres and spectra, including complex but essential NLTE and 3D corrections. The analysis pipeline for the SDSS V Milky Way Mapper survey is being developed at Monash University, where we have built up substantial capacity for processing millions of IR spectra to derive stellar parameters and abundances.

We also have significant local expertise in developing data-driven analysis methods based on clustering, machine learning and neural networks. These methods have already become well embedded in astronomical research, and will be essential for discovery of both underlying structure and outliers in large new data spaces. Continued technology development in high-performance hardware, AI algorithms, and potentially quantum computing will continue to provide us with better tools over the next decade. Novel data analysis work also provides excellent opportunities for training students and ECRs for both research and industry careers.

Theme D: Enabling factors

The idea of integration has arisen in a number of contexts in WG1.2 discussions. In the research sphere, we see the integration of research across size scales (planets to stars, stars to galaxies) and across methodologies (radio and optical, observation and theory, Galactic and extragalactic) as key to more impactful research outcomes. We also see opportunities for more interaction and collaboration within the research community. One major impact of the ARC Centre of Excellence program on the astronomical community has been to increase the number and diversity of research connections. This has led to tangible benefits for the research communities within the reach of the CAASTRO, ASTRO 3D, and OzGrav CoEs, and the broader community should learn from this positive experience.

Integration for research success

In all of the science areas under the WG1.2 umbrella, there is a clear movement toward research questions and tools that cross methodological gaps, and we welcome new opportunities to connect theory to observations that will arise from growth in multi-wavelength and multi-messenger data. This is visible in our key research questions: in our view, considering planetary systems, their host stars, and the Solar System together will give us the best opportunity to understand the underlying astrophysics and astrobiology. We connect the forging of heavy elements in specific astrophysical sites with gas cycling and the formation of new generations of stars in a galaxy environment so that we can accurately interpret and predict those larger-scale systems.

We expect that an integrated approach to research in the next decade will bring an ability to address broader and more impactful research questions, novel approaches with less duplication of effort, and a more constructive and equitable working environment. The astronomical research community should actively foster fluency and collaboration across fields. Ideally this would leverage the venue provided by the ASA Annual Science Meeting, in the traditional in-person and newer remote and virtual spaces, and create new opportunities for our community to learn from each other. The annual conference and summer school organised by the ANITA chapter of the ASA is a good example of this kind of cross-communication, and the ASA ECR Chapter has done excellent work to provide professional development, community, and broader exposure for junior researchers. Direct support from the ASA, perhaps in the form of a professional staff member with a focus on facilitating collaboration, could help the community to build on this strong base.

Infrastructure for collaboration

Easier and broader collaboration are important for transcending the limited size and research scope of any given institution. Australian astronomy groups must have a certain level of diversity in research areas and skillsets to train a wide array of students and attract regular research funding. This tends to produce a "one of everything" population of long-term academic staff in each group, making it difficult to build critical mass in any particular research area at any one institution.

New venues for sharing ideas, in particular work in progress, could be very helpful in facilitating cross-institutional and cross-specialty collaboration. Shifting the effort for organising workshops and co-working time off of researchers is a simple change that could make a major impact on the number and effectiveness of such events. Widely accessible data archives with the ability to process data on-site and share the results with selected collaborators would also make a major impact on our ability to work closely, even at a distance. In principle the resources for this exist; as noted under Theme C, these resources need to expand and increase their interoperability and ease of use in the coming decade.

People power: career paths, capacity building, equity and inclusion

Upcoming projects like SKA and LSST have done explicit planning for data storage, transmission, and processing because of their massive scale. With SKA, we will have far more data and opportunity than we can currently understand, and the human and computing resources for handling the data need to be prioritised at the same level as the facilities.

Among researchers it is well understood that people with specialised technical skills are essential for the success of our work. Australian astronomy has been a long-time world leader in technologies like fibre multiplexing because of close collaborations between scientists and engineers; to maintain a leading role in a data-rich research era we must make software and data engineers similarly central to our research organizations. Universities, observatories, and CSIRO will all need to create appropriate promotion and retention pathways for the people with these skillsets in order for our research accomplishments to reach their potential. The community also needs a coordinated approach to maintain an appropriately stable pipeline for those skillsets.

We also cannot be successful without respectful workplaces that actively strive to become more positive environments. We have moved on from the era of Ruby Payne-Scott's unceremonious ejection from a research career, but our community is not representative of broader Australian society, nor of the young people who aspire to be scientists. We also continue to fall into traps of overwork and a scarcity mindset, with significant negative impacts on mental health and work-life balance. Senior astronomers should all act on the responsibility to reshape their institutions and professional organisations to provide opportunities and rewards in a more equitable way. The ASA IDEA chapter's Pleiades awards have surfaced both excellent practices and lingering issues, and we must use that information to improve our working environments.

Appendix 1: Working Group process

The Working Group on Stars, Planets and the Milky Way held a series of town hall-style meetings for community consultation in early 2024. These meetings were divided by research topics and methodologies (exoplanets, radio observations, optical/IR observations, theory, survey science) to allow for discussions with more specificity and depth. These meetings were advertised to the membership of the Astronomical Society of Australia via the general mailing list, with an encouragement to pass the invitation on to non-ASA members, and key people from outside the ASA membership invited to participate by the topical sub-leads. Different subsets of the community were in attendance at each meeting.

We also advertised an online survey as an input channel for those who were not able or interested to join the online meetings, or for those who wanted to give more extended written comments. We received thirteen responses.

Following the meetings, the topical leads each wrote up a summary of the discussions in four major directions (progress against the previous Decadal Plan, major science themes for the next decade, key opportunities and challenges, and enabling strategies and resources) as well as other topics that arose during the conversation. Separate to this, members of the exoplanet community wrote up white papers on planetary atmospheres and demographics. These are attached in Appendix 2.

The text in this paper is partially adapted from the survey responses, topical summaries, and contributed white papers.

Appendix 2: Contributed white papers

Australian Exoplanet Demographics Exploration 2026-2035

White paper submitted to the Stars, Planets, and the Galaxy Working Group [1.2] for the Decadal Plan for Australian Astronomy 2026-2035

Authors: Chelsea X Huang [UniSQ], George Zhou [UniSQ], Yuan-Sen Ting [ANU/OSU], Simon J. Murphy [UniSQ], Benjamin Pope [UQ], Robert A. Wittenmyer [UniSQ], Jonti Horner [UniSQ], Daniel J. Price [Monash] Et al.

Co-signers: Duncan Wright [UniSQ], Melissa Ness (ANU/Columbia), Fan Liu [Monash], Belinda Nicholson [UniSQ], Daniel Huber (Sydney/Hawai'i)... YYY et al.

Key science questions

- How common are solar systems like our own, and what other kinds are there?
- How do the characteristics of stars influence the planetary systems they host?
- How do planetary systems form and evolve?

Key recommendations

- Promote the development of a new generation of scientists specialized in statistics and machine learning who would best utilize new planet demographics and stellar population surveys in the next decade, via strategic allocation of research funding towards data analysis method oriented projects.
- Prioritise retaining membership in ESO, Australia's only major ground-based optical facility capable of characterizing Earth-like planets.
- Pursue the development of a new generation of Australian-led space and ground-based facilities, and Australian partnership in international collaborations enabling the detailed characterisation of analogs of Solar system planets.
- Push for domestic high-precision radial velocity facilities to support mass measurements of planet demographics surveys.
- Promote diversity, equity and inclusion within the Australian exoplanet community.

How do planets form and grow? Where do planet formation and migration occur? Did the same processes that shaped Solar system also sculpt the thousands of other planets we have now found orbiting other stars?

How common are solar systems like our own, and what other kinds are there?

The understanding of planets around other stars has advanced at an astonishing speed in the international stage since the Nobel Prize-winning discovery of the first exoplanet in 1995. However, among the many planetary systems so far discovered, our Solar System remains unique: it hosts planets with masses and orbital periods ranging over three orders of magnitude. The system architecture of the Solar system encodes the hidden history of its origin: Jupiter and Saturn were responsible for the low mass of Mars, the eccentric orbit of Mercury, and oceans on Earth (Bromley & Kenyon, 2017; Laskar, 2008; Raymond et al., 2006). To connect the population of exoplanets to the Solar System directly, we need to not only discover and characterise individual planets, but also study the properties of entire extrasolar planetary systems. These planetary systems can only be studied by employing multiple planet discovery and characterisation techniques simultaneously.

Maximize Australian-led science in current and future exoplanet demographics surveys

The next decade will see multiple large exoplanet survey missions that will use different techniques to probe different regions of exoplanetary systems. NASA's *TESS* mission is revealing exciting aspects of new close-in planet populations (Huang et al., 2020; Luque et al., 2023; Vach et al., 2024a; Zhou et al., 2019a), and will continue to survey the entire sky. ESA's *Gaia* mission and NASA's *Nancy Grace Roman Space Telescope* will revolutionize our understanding of long period planets (Johnson et al., 2021; Perryman et al., 2014). In addition, *Roman* is expected to conduct the first transit survey of the Galactic bulge (Wilson et al., 2023), providing opportunities to significantly advance our understanding of exoplanet demographics across stellar populations and Galactic environments. Australia is also a partner of the Vera C. Rubin Observatory, which will discover a large number of transiting planets around stellar populations that are not typically surveyed (i.e. white dwarfs; Lund et al., 2018), and deliver the first knowledge of populations of planets in the LMC (Jacklin et al., 2015). More conventional transit planet surveys studying long period ($P \sim 1$ yr) planets are also expected to be launched (PLATO: Rauer et al., 2024) or in the final phase of planning (Earth 2.0: Ge et al., 2022).

These surveys provide the first major opportunities to study planetary system architecture using overlapping discovery spaces and different planet detection techniques. We have already witnessed how the overlap between the transit and radial velocity techniques has revolutionised our understanding of exoplanet compositions (Parc et al., 2024). One of the most promising overlapping discovery spaces in the near future will be planetary systems detectable with NASA's *TESS* mission and ESA's *Gaia* mission, the two most powerful wide-field all-sky surveys to date. These planetary systems will have their inner planets detectable with *TESS*, and their outer planets detectable via *Gaia* astrometry (Figure 1), enabling population-level studies of planetary system architecture.

In the coming decade, Australian scientists have rich opportunities to establish leadership in these major exoplanet demographics surveys. As demonstrated by *TESS*, modern surveys with open data policy enable well-prepared teams all over the globe to capitalize on their science output. These survey missions are expected to adopt an open data policy similar to *TESS*, or have relatively short proprietary periods[1] [2].

Australian scientists are well-positioned to lead in the field of exoplanet demographics using modern statistical and AI approaches. Our community's strengths in stellar astrophysics, particularly in characterizing stellar chemistry (e.g., the GALAH survey, De Silva et al. 2015) and asteroseismology (e.g. Bedding et al., 2020; Huber et al., 2011, 2013a; Murphy et al., 2019), provide a solid foundation for this work. These areas are crucial for determining key stellar properties, especially ages, which are vital for studying not only exoplanet formation but also their evolution,

---

[1] Although the Gaia mission has a relatively long proprietary period, the community is able to significantly contribute to its science output due to the sheer volume of data.

[2] Roman is expected to release 90% of the calibrated data within a week of acquisition.

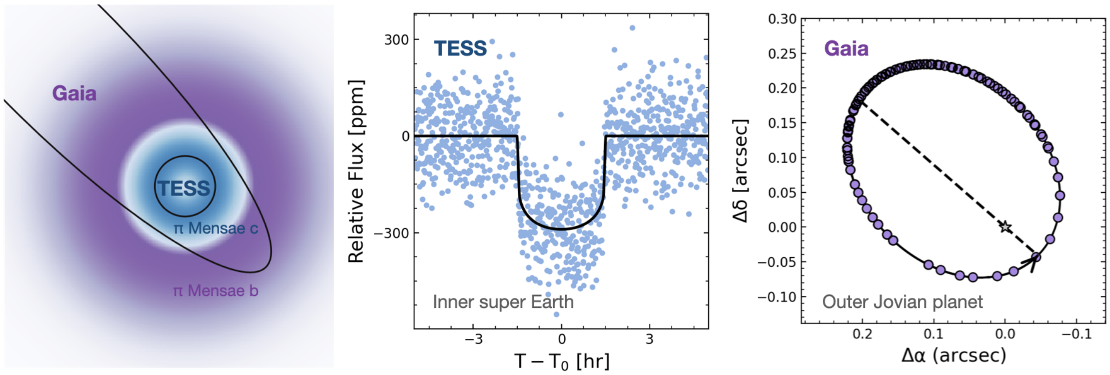

Figure 1: **Left**: sketch of planets' orbits (not to scale) in the π Mensae planetary system. The inner blue region represents the planet discovery space of *TESS*; the outer purple region represents the planet discovery space of *Gaia*. Combining both will allow us to study the full architecture of exoplanetary systems. **Centre**: the inner super Earth π Mensae c was discovered by the *TESS* mission via the transit method (Huang et al., 2018). The blue data points are phase folded *TESS* observations. **Right**: The orbit of π Mensae b (originally discovered via the radial velocity method as part of the Anglo-Australian Planet Search, (Tinney et al., 2001)) will also be measured with the *Gaia* data. The purple points are simulated *Gaia* data based on realistic *Gaia* observation epochs. Figure Credit: C. X. Huang.

including potential ejection or engulfment throughout a star's lifetime (Liu et al., 2024)

The complex physics involved in stellar characterization, whether through spectral analysis or time-series light curves, has inspired the **development of specialized machine learning tools** (Casey et al., 2016; Ness et al., 2015, 2013; Pan et al., 2024, 2023; Różański et al., 2024). Further, the study of how exoplanet orbits evolve and the stability of planetary systems based on their current orbits also constitutes the cutting edge of research through the lens of machine learning (Tamayo et al., 2016, 2020). This area represents a growing and vibrant field of research within astrophysics, distinct from typical industry-developed machine learning applications like computer vision.

Investing in training the next generation of scientists to lead projects in large-scale exoplanet demographic surveys will equip our astronomy students with valuable computational and data science skills. These skills not only advance our understanding of exoplanets but also reinforce Australia's workforce in software and information technology. As highlighted in the US Decadal Survey 2020, astronomy training provides vital skills for students pursuing both professional astronomy and non-astronomy STEM careers, contributing to Australia's broader technological capabilities.

Detailed characterisation of analogs of Solar System planets

High-precision radial velocity instruments such as **Minerva-Australis** (Addison et al., 2019) and **Veloce on the AAT** will continue to be important in understanding the detailed characteristics of planets detected through the various planet surveys, to measuring the bulk composition of transiting planets, and to complementing Gaia astrometric orbits. Gaia's Non-Single-Star (NSS) two-body orbit catalog (Halbwachs et al., 2023; Holl et al., 2022) published within DR3 (Gaia Collaboration et al., 2023) contains astrometry-based orbital solutions for approximately 450 000 stars around each system's centre of mass. The astrometry and RV information are orthogonal. Hence, this powerful combination will for the first time enable us to determine the full 3-D architecture of Jupiter-analog systems (Figure 2).

Next-generation instruments on the **VLT Interferometer** (e.g. GRAVITY+ and the Australian-led Asgard; Gravity+ Collaboration et al., 2022; Taras et al., 2024) and **ELTs (such as the Giant Magellan Telescope Near Infrared Spectrograph [GMTNIRS], ELT-CAM and EELT-IFU)** will provide the capability to directly image the companions causing these orbital motions detected by Gaia (Figure 3). Just as radial velocity follow-up provides independent confirmation and additional characterisation of transiting planets, a subsequent detection of the companion with direct imaging can confirm the candidate and provide the dynamical mass, and a direct measurement of its luminosity and spectrum.

How do the characteristics of stars influence the planetary systems they host?

Understanding the characteristics of planet-hosting stars is crucial for unravelling the complexities of planet formation and evolution. The formation of planets depends on various factors, notably stellar metallicity (Ghezzi et al., 2018; Haywood, 2009; Zhu, 2019), but also the influence of close binaries (Kraus et al., 2012; Moe & Kratter, 2021) and the galactic environment in which stars form (Winter et al., 2020). However, some of these factors, such as the binary fraction of stars and how it changes for different stellar populations across stellar ages and galactic components, remain largely understudied.

Stellar abundances have proven to be valuable indicators of exoplanet properties that are otherwise difficult to assess (Clark et al., 2022). For instance, studies of white dwarfs and their chemical anomalies have shed light on the elemental abundances of planets before they were disrupted by the white dwarf's gravitational potential (Gänsicke et al., 2012; Hollands et al., 2018; Rogers et al., 2024). Similarly, both planet formation and the orbital evolution of exoplanets have been shown to generate subtle chemical differences in stars, which can be studied through the comparison of stellar twins (Liu et al., 2020; Liu et al., 2024; Meléndez et al., 2012). The study of Solar analogs has also illuminated many of the anomalous properties of our own Solar System, potentially tracing back to its formation process.

Characterizing stellar ages and studying the statistics of exoplanet populations for different stellar populations and formation environments holds the key to understanding not only the formation phase of exoplanets but also their subsequent evolution (Chen et al., 2024).

The continued investment in at least one of the **20-30 m class telescopes** will be critical for such research. The debate on the abundance-exoplanet connection remains inconclusive due to limited abundance accuracy in current spectroscopic surveys. High signal-to-noise ratio (S/N) spectra with high resolution remain scarce, and this issue will persist even with next-generation spectroscopic surveys including 4MOST and WEAVE, as these are either limited in their plans to observe a "golden sample" in the solar neighbourhood with high S/N and long exposure times, or they are limited in resolution to cater to cosmological studies.

Australia is uniquely positioned to lead this field of study. Not only does Australia have decades-long expertise in abundances retrieving (e.g. De Silva et al., 2013, 2007; Frebel et al., 2005; Nandakumar et al., 2022; Ness et al., 2013), but it is also pushing the frontier in much of the stellar modelling from first principles (e.g., 3D non-local thermodynamic equilibrium [NLTE] modelling of stellar spectra, (Bergemann et al., 2017)), which remains one of the key limitations to achieving sub-0.03 dex precision in abundance measurements (see Jofré et al. (2019) for review).

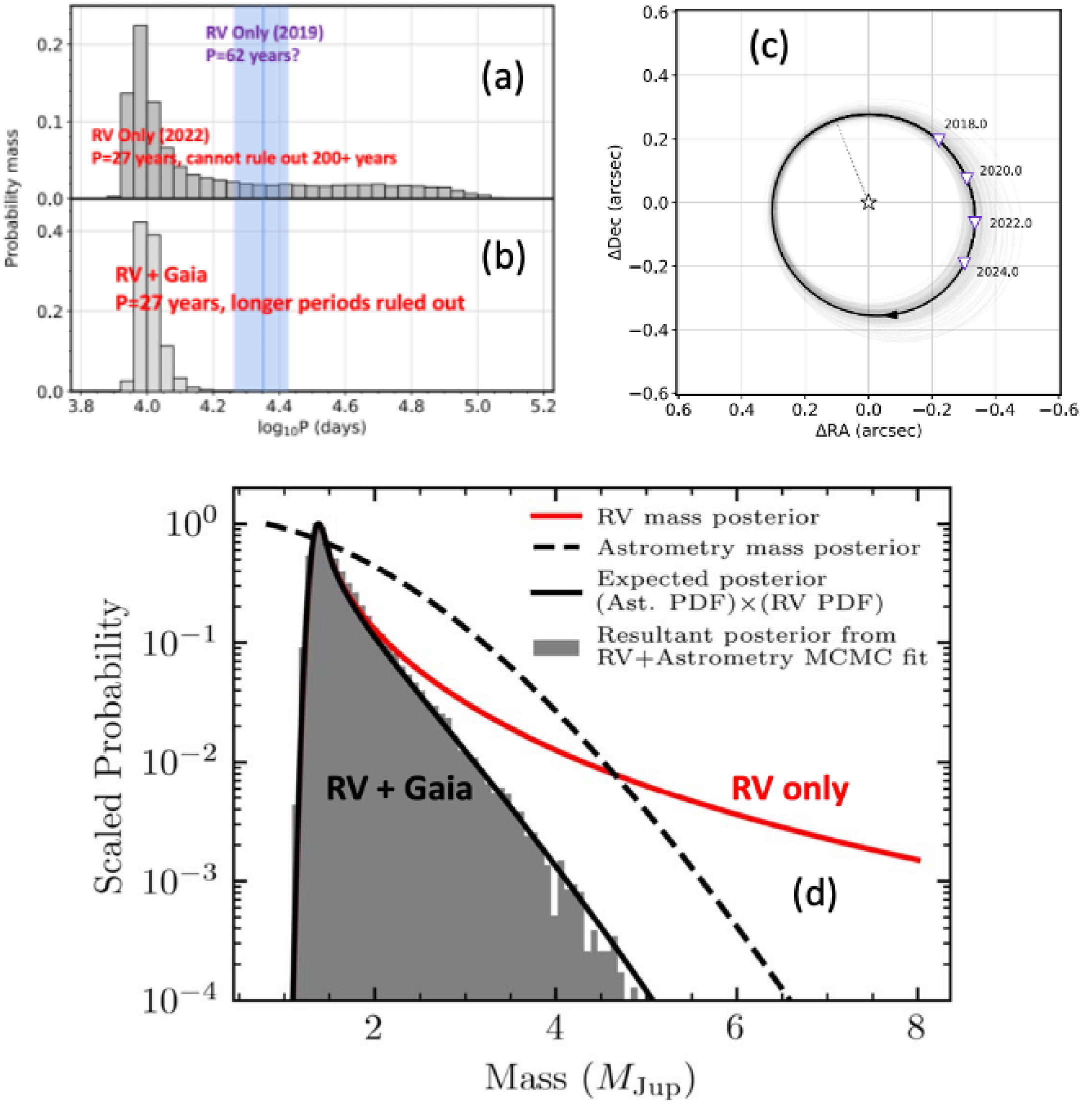

Figure 2: **Top right**: Orbital period determination for the giant planet HD 221420b, showing the significant improvement due to the inclusion of astrometric information (Venner et al., 2021). **Top left**: Orbital motion on-sky for HD 221420b; the system is nearly face-on as viewed from Earth. **Bottom**: The grey region shows the added constraints afforded by including the Gaia non-detection for HD 83443c, another long-period cold giant planet (Errico et al., 2022). Astrometry provides valuable information even when the planet is not detected. Figure Credit: R. Wittenmyer.

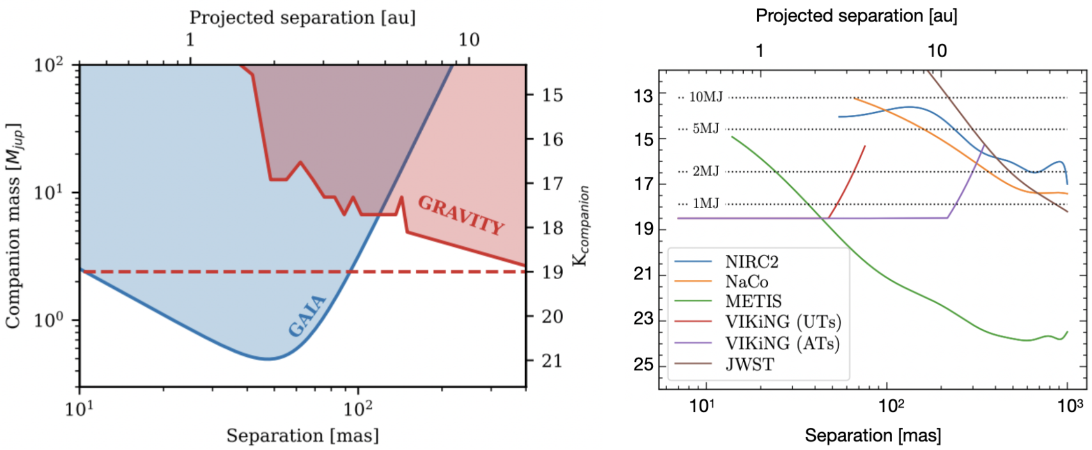

Figure 3: **Left:** Sensitivity of VLT/GRAVITY compared to the detection parameter space of ESA/GAIA (Pourré et al., 2024); **Right:** Assumed limits for other current and future instruments direct imaging instruments. Figure adapted from Wallace et al. (2021). Minor modification is made to the figure so that it has similar axes to the left Figure.

Many exoplanet signals are expected to be hidden at this scale.

Moreover, the characterization of stellar populations, including binarity, the secular evolution of the Milky Way, and the connection to star formation environments at earlier times, could have significant implications for planet formation (Murphy et al., 2016, 2018). The ongoing GALAH survey and Australia's participation in 4MOST and WEAVE will prove critical in such endeavours.

How do planetary systems form and evolve?

Planet formation

Planet formation is a subject that since 2015 has been revolutionised by the ability to resolve substructures inside the discs of gas and dust around young stars. First light images with the ALMA telescope (ALMA Partnership et al., 2015) revealed a series of rings and gaps in the protostellar disc around HL Tauri. Much speculation has ensued regarding the origin of these substructures, but there is now widespread consensus that at least *some* of the gaps are carved by protoplanets, in a process analogous to that seen in Saturn's rings (Ayliffe et al., 2012; Dipierro et al., 2015; Jin et al., 2016). Direct imaging has found planets in gaps in the discs around PDS 70 (Keppler et al., 2018; Müller et al., 2018) and HD 169142 (Hammond et al., 2023) with several other possible candidates. Complementary observations in ALMA line emission have revealed localised velocity perturbations (Pinte et al., 2018, 2019, 2020; Verrios et al., 2022) that match model predictions for the wakes generated by embedded Jupiter-mass planets (Bollati et al., 2021; Calcino et al., 2022; Verrios et al., 2022). Australia has led much of the work on kinematic detection of planets (Pinte et al., 2023a), including co-leading the major exoALMA large program dedicated to characterising the velocity substructures observed in protoplanetary discs with a view to detecting planets.

In principle, disc kinematics can directly constrain the planet mass. More strictly, these measurements probe the planet mass in units of the thermal mass

$$M_{\rm thermal} \equiv \frac{4}{3}\pi \left(\frac{H}{R}\right)^3 M_*,$$

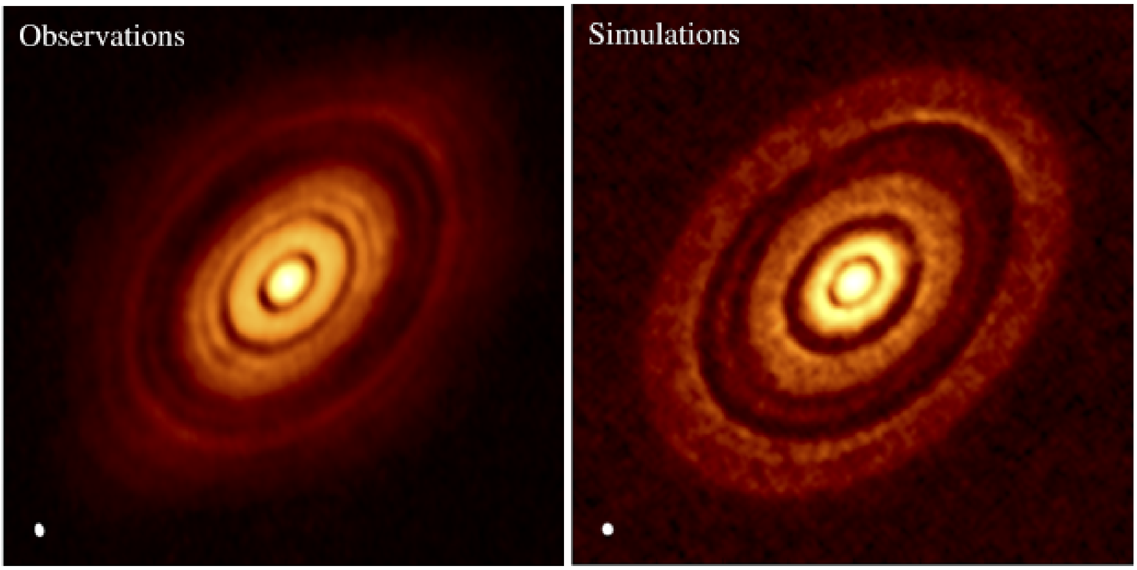

Figure 4: Gaps and rings in the disc around HL Tau seen in first-light observations at mm-wavelengths with ALMA (left), and their interpretation in terms of 3 embedded Jupiter-mass protoplanets from hydrodynamical simulations (right) (Dipierro et al., 2015).

where H/R is the disc aspect ratio (Bollati et al., 2021). Thus, precise characterisation of the disc thermal structure is required for a true planet mass, but this is also possible by careful fitting to ALMA observations (Calcino et al., 2022).

By combining direct imaging with disc kinematics one is able to simultaneously constrain both the mass and luminosity of embedded planets. This is crucial for planet evolution models and for the predicted luminosity of planets at young ages, since planets cool as they age. one can also directly constrain the growth mechanism of planet envelopes, their mode of accretion and the presence and structure of circumplanetary material. Evidence for circumplanetary material has been presented for PDS70 b in the form of infrared excess at 3 microns (Christiaens et al., 2019). PDS70 c shows direct evidence for a circumplanetary disc in mm-continuum emission with ALMA (Benisty et al., 2021). Tentative simultaneous detection of an embedded planet in both kinematics and direct imaging, suggestive of an actively accreting planet heating its surroundings and with a local velocity gradient indicative of a circumplanetary disc (Pinte et al., 2023b). Similarly, detection of HD 169142 b in polarised light suggests an envelope of material surrounding the planet that scatters light from the central star (Hammond et al., 2023).

That such massive (super Jupiter) planets appear to exist at the earliest ages that we can observe protoplanetary discs is challenging our ideas about planet formation. For example, there is broad consensus that a 10 Myr timescale for giant planet formation predicted by traditional core accretion models is no longer viable. However, ideas like pebble accretion show that this timescale may be greatly accelerated even on theoretical grounds. Observations of young planets are consistent with hot start formation, which may indicate gravitational instability as a viable mechanism. Indeed, there are now several claims of observed gravitationally unstable discs, including Elias 2-27 (Hall et al., 2018; Paneque-Carreño et al., 2021), AB Aur and IM Lup (Lodato et al., 2023), mainly based on the morphology of observed spiral structure, although other explanations are possible (e.g. embedded planets; Meru et al. 2017; Verrios et al. 2022).

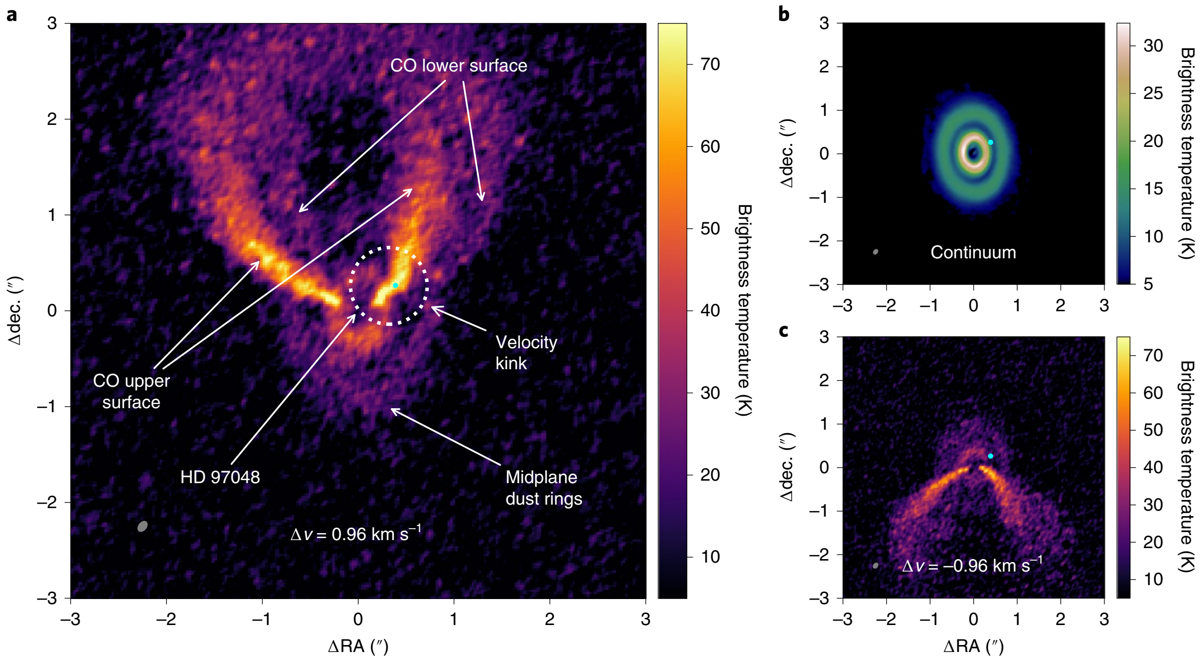

Figure 5: Kinematic detection of a planet carving a gap in a protostellar disc, showing the localised velocity perturbation (labelled 'Velocity kink') in Doppler-shifted CO emission (left), co-incident with a planet located in a gap in the continuum emission (top right). Bottom right panel shows the channel map on the other side of the disc, with no corresponding perturbation (Pinte et al., 2019).

The next frontiers in this field are i) to understand the connection between planet forming discs and their environment — since it is clear from observations of late infall, accretion streamers and stellar flybys (Cuello et al., 2023) that the two are connected; ii) looking for chemical signatures of planets by observing more complex molecules including SO and H_2O; iii) obtaining resolved observations of more compact discs typical of the solar system and iv) obtaining cm-wavelength follow-up with radio telescopes to see how the pebble-sized material is distributed, more directly constraining the pebble accretion hypothesis in particular. An example of the latter is the 'Discs Downunder' survey comparing observations with ATCA to those at ALMA wavelengths (Norfolk et al., 2021).

For Australia to continue its leading role in this area, three things are needed:

1. Time on the ALMA telescope and VLT/SPHERE via full membership of ESO, along with access to ELT-class telescopes once they come online, as these will further revolutionise our ability to image young planets, probe their surrounding environment and resolve the more compact sources.
2. Continued investments in theory and astronomy-specific computational facilities — the OzSTAR facility at Swinburne has proved particularly enabling for this work.
3. 1000-hr time allocations on SKA-mid (Ilee et al., 2020), combined with a large-scale upgrade to ATCA to enable cm-wavelength follow up at comparable spatial resolution and sensitivity to ALMA, similar to what is planned for the ngVLA, but in the Southern hemisphere.

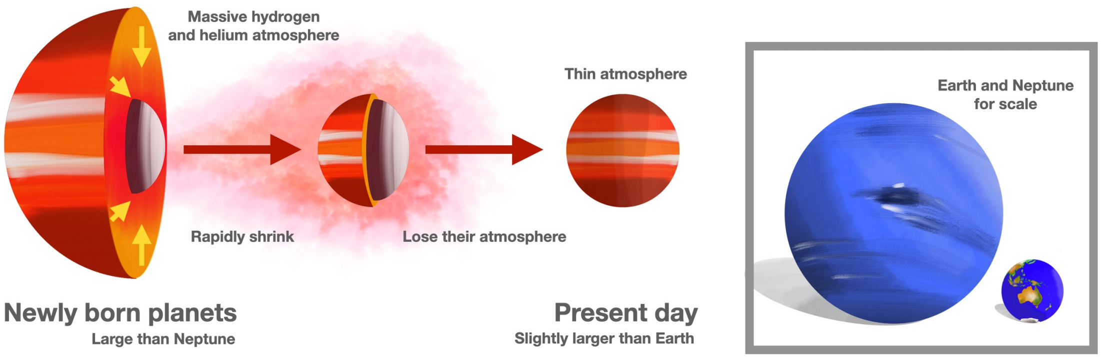

Figure 6: Sketch of processes affecting planets' radius evolution (credit: G. Zhou).

Planet radius evolution

The most common planets in our galaxy are Super-Earths or Neptune-sized planets (planets with sizes between 1-4 Earth radius) orbiting close-in to their stars. It is believed that similar to the Earth, these planets originally had a thick hydrogen-helium atmospheric envelope that evaporated into space within their first 500 million years as a result of intense X-ray and UV irradiation from their young host star. In the case of Earth, this was accompanied by atmospheric replenishment from active volcanism, but it is not currently known whether this mechanism is common for Super-Earths or Neptune-sized planets.

We expect the fundamental properties of planets, such as their radii, to evolve dramatically during the first hundred million years of their formation. Many planets are expected to rapidly lose their outer hydrogen–helium envelopes post-formation, leading to a 10% reduction of their mass, and 75% reduction of their radius (Owen & Wu, 2017). Such dramatic radius evolution should be visible if we examine the planet population around young stars. However, few such young planets are known today. Young planets are rare, as they encompass only a small time frame in the lifetime of planets, and they are technically difficult to detect.

Most models show that planets evolve rapidly in the first hundred million years (e.g. Kubyshkina et al., 2018). In particular, most planets that orbit close-in to their stars undergo exponential 'runaway mass-loss' during this time frame. As the planets lose their outer gaseous envelopes, they will also experience significant reductions in their sizes. Using TESS's all-sky survey data to date, and following techniques from Zhou et al. (2019b), Vach et al. (2024b) detected tentative signs that the planet radius distribution is shifted to larger radii for planets younger than 200 Myrs. As TESS continues its all-sky survey, it will provide the largest sample of young stars to understand the true occurrence rates of the planets as a function of their radius and age, as well as the initial envelope-mass fraction of these primordial planets. New age determination methods making use of the combination of stellar rotation period and their kinematics (Lu et al., 2021) will provide accurate average age for a large number of stars, opening up possibilities to track planet evolution beyond Gyrs.

Planet orbital obliquity evolution

The orbital obliquities distribution is another key tool to probe the dynamical histories of exoplanets and exoplanetary systems. Are planets born misaligned, or do they become misaligned later

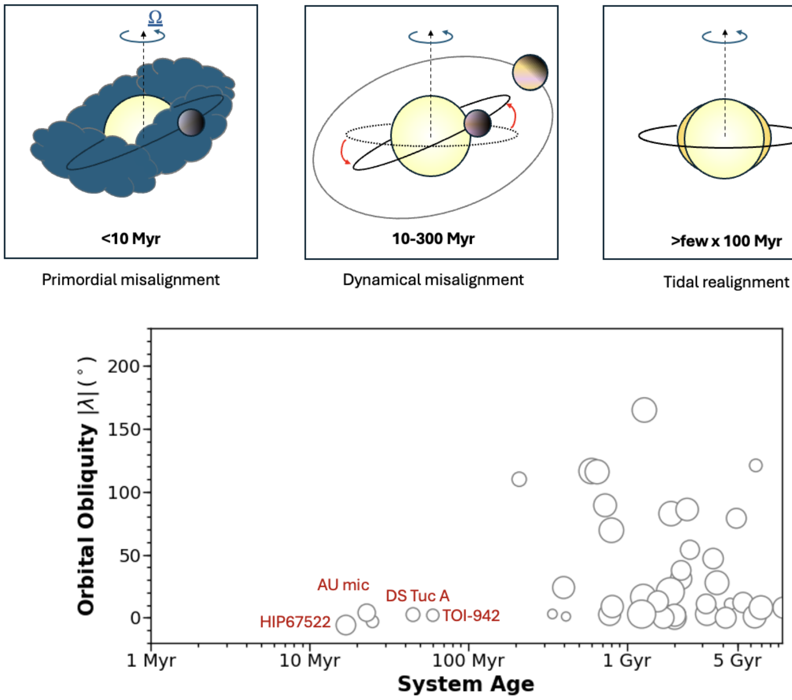

Figure 7: Top: sketch of processes that affect planets' orbital obliquities and their respective time scales (credit: S. Murphy). Bottom: Projected stellar obliquity versus estimated stellar age (credit: G. Zhou). Red labels mark publications led by Australian teams.

through dynamical interactions? What processes during planet formation and migration impact their orbital obliquities? Within the next decade we will have the capability to measure the orbital obliquities of a large population of small planets at different ages, and to trace how, when, and where planet formation and migration occurs.

Measuring the obliquities of individual planets within multi-planetary systems can also help us probe their overall dynamical histories through characterizing their mutual inclinations. The mutual inclinations of planetary systems encode both planet-disk and planet-planet interactions. For compact super-Earth systems, the mutual inclination distribution can yield insights into the gas environments in which they were formed (Dawson et al., 2016). Planet-planet interactions post gas-dissipation are also thought to excite the inclinations of close-in planets (e.g. Hansen & Murray, 2013), potentially leading to the large mutual inclinations of systems with close-in companions (Dai et al., 2018). For compact systems of super-Earths and Neptunes, companion Jovian planets are thought to excite the mutual inclination and dynamically destabilize the inner planets (Becker & Adams, 2016). In the era of Gaia, we expect an abundance of exterior Jovian planets with interior transiting companions that will be suitable for obliquity measurements.

Australian teams are pioneering techniques to determine the obliquity of protoplanetary disks using stellar pulsations for the first time (e.g. Huber et al., 2013b; Murphy et al., 2021), and have been leading obliquity measurements of the youngest planets (e.g. Heitzmann et al., 2021; Montet et al., 2020; Wirth et al., 2021; Zhou et al., 2020). Over the coming decade, the next generation of ground-based facilities will come online. The **ELTs** will have unprecedented light-gathering power, coupled with state-of-art highly stabilized high-resolution spectrographs (e.g. Szentgyorgyi et al., 2016). These facilities offer new possibilities to explore the obliquities of small transiting planets that are out of reach of today's instrumentation. Hundreds of small planets will be suitable for spectroscopic obliquity measurements in the near future. Missions like TESS and PLATO are designed to deliver small planets around bright stars that are suitable for follow-up observations.

Promote diversity, equity and inclusion within the Australian exoplanet community

The international exoplanet field has reached important milestones in gender representation. In the three major exoplanet international conferences in 2024, the fraction of female speakers reached near equity. Specifically, in Extreme Solar System V and Exoplanets 5, 44% and 46% of the plenary talks are awarded to female presenters, respectively. Of the exoplanet-topical speakers at TESS Science conference III, 56% identified as female. Racial and ethnic diversity remain poorly addressed in the community.

As a young and emerging field in Australia, there is the opportunity to promote diversity, equity and inclusion while we expand the exoplanet field in the next decade. As a pathway forward, we would like to recommend:

- Funding agencies such as the ARC increase the number of awards that invest in the development and retention of early and mid-career faculties and other activities for members of underrepresented groups.
- Australian Exoplanet research groups to prioritize the research participation of underrepresented groups from the HDR stage onward.
- Australian Exoplanet conferences to set up travel awards to encourage the participation of earlier-career researchers, prioritising members from underrepresented groups.

References

Addison et al. 2019, PASP, 131, 115003
ALMA Partnership et al. 2015, ApJ, 808, L3
Ayliffe et al. 2012, MNRAS, 423, 1450
Becker & Adams. 2016, MNRAS, 455, 2980
Bedding et al. 2020, Nature, 581, 147
Benisty et al. 2021, ApJ, 916, L2
Bergemann et al. 2017, ApJ, 847, 15
Bollati et al. 2021, MNRAS, 504, 5444
Bromley & Kenyon. 2017, AJ, 153, 216
Calcino et al. 2022, ApJ, 929, L25
Casey et al. 2016, arXiv e-prints, arXiv:1603.03040
Chen et al. 2024, Constraints on the formation history and composition of Kepler planets from their distribution of orbital period ratios, , , arXiv:2406.08794
Christiaens et al. 2019, ApJ, 877, L33
Clark et al. 2022, MNRAS, 510, 2041
Cuello et al. 2023, European Physical Journal Plus, 138, 11

Dai et al. 2018, ApJ, 864, L38
Dawson et al. 2016, ApJ, 822, 54
De Silva et al. 2013, MNRAS, 431, 1005
—. 2007, AJ, 133, 1161
—. 2015, MNRAS, 449, 2604
Dipierro et al. 2015, MNRAS, 453, L73
Errico et al. 2022, AJ, 163, 273
Frebel et al. 2005, Nature, 434, 871
Gaia Collaboration et al. 2023, A&A, 674, A1
Gänsicke et al. 2012, MNRAS, 424, 333
Ge et al. 2022, arXiv e-prints, arXiv:2206.06693
Ghezzi et al. 2018, ApJ, 860, 109
Gravity+ Collaboration et al. 2022, The Messenger, 189, 17
Halbwachs et al. 2023, A&A, 674, A9
Hall et al. 2018, MNRAS, 477, 1004
Hammond et al. 2023, MNRAS, 522, L51
Hansen & Murray. 2013, ApJ, 775, 53
Haywood. 2009, ApJ, 698, L1
Heitzmann et al. 2021, ApJ, 922, L1
Holl et al. 2022, A&A, 661, A151
Hollands et al. 2018, MNRAS, 477, 93
Huang et al. 2018, ApJ, 868, L39
—. 2020, ApJ, 892, L7
Huber et al. 2011, ApJ, 743, 143
—. 2013a, ApJ, 767, 127
—. 2013b, Science, 342, 331
Ilee et al. 2020, MNRAS, 498, 5116
Jacklin et al. 2015, AJ, 150, 34
Jin et al. 2016, ApJ, 818, 76
Jofré et al. 2019, ARA&A, 57, 571
Johnson et al. 2021, in American Astronomical Society Meeting Abstracts, 237American Astronomical Society Meeting Abstracts, 218.09
Keppler et al. 2018, A&A, 617, A44
Kraus et al. 2012, ApJ, 745, 19
Kubyshkina et al. 2018, A&A, 619, A151
Laskar. 2008, Icarus, 196, 1
Liu et al. 2020, MNRAS, 495, 3961
Liu et al. 2024, Nature, 627, 501–504
Lodato et al. 2023, MNRAS, 518, 4481
Lu et al. 2021, AJ, 161, 189
Lund et al. 2018, arXiv e-prints, arXiv:1809.10900
Luque et al. 2023, Nature, 623, 932
Meléndez et al. 2012, A&A, 543, A29
Meru et al. 2017, ApJ, 839, L24
Moe & Kratter. 2021, MNRAS, 507, 3593

Montet et al. 2020, AJ, 159, 112
Müller et al. 2018, A&A, 617, L2
Murphy et al. 2016, ApJ, 827, L17
—. 2019, MNRAS, 485, 2380
—. 2021, MNRAS, 502, 1633
—. 2018, MNRAS, 474, 4322
Nandakumar et al. 2022, MNRAS, 513, 232
Ness et al. 2015, ApJ, 808, 16
—. 2013, MNRAS, 430, 836
Norfolk et al. 2021, MNRAS, 502, 5779
Owen & Wu. 2017, ApJ, 847, 29
Pan et al. 2024, arXiv e-prints, arXiv:2405.17156
—. 2023, arXiv e-prints, arXiv:2309.16316
Paneque-Carreño et al. 2021, ApJ, 914, 88
Parc et al. 2024, arXiv e-prints, arXiv:2406.04311
Perryman et al. 2014, ApJ, 797, 14
Pinte et al. 2023a, in Astronomical Society of the Pacific Conference Series, 534Protostars and Planets VII, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 645
Pinte et al. 2018, ApJ, 860, L13
—. 2019, Nature Astronomy, 3, 1109
—. 2020, ApJ, 890, L9
—. 2023b, MNRAS, 526, L41
Pourré et al. 2024, A&A, 686, A258
Rauer et al. 2024, arXiv e-prints, arXiv:2406.05447
Raymond et al. 2006, Science, 313, 1413
Rogers et al. 2024, MNRAS, 527, 6038
Różański et al. 2024, arXiv e-prints, arXiv:2407.05751
Szentgyorgyi et al. 2016, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 9908Ground-based and Airborne Instrumentation for Astronomy VI, ed. C. J. Evans, L. Simard, & H. Takami, 990822
Tamayo et al. 2016, ApJ, 832, L22
—. 2020, Proceedings of the National Academy of Science, 117, 18194
Taras et al. 2024, Appl. Opt., 63, D41
Tinney et al. 2001, ApJ, 551, 507
Vach et al. 2024a, AJ, 167, 210
—. 2024b, AJ, 167, 210
Venner et al. 2021, AJ, 162, 12
Verrios et al. 2022, ApJ, 934, L11
Wallace et al. 2021, MNRAS, 508, 2515
Wilson et al. 2023, ApJS, 269, 5
Winter et al. 2020, Nature, 586, 528
Wirth et al. 2021, ApJ, 917, L34
Zhou et al. 2019a, AJ, 158, 141
—. 2019b, AJ, 158, 141
—. 2020, ApJ, 892, L21

Zhu. 2019, ApJ, 873, 8

Australian Exoplanet Atmospheres Exploration 2026-2035

White paper submitted to the Stars, Planets, and the Galaxy Working Group [1.2] for the Decadal Plan for Australian Astronomy 2026-2035

Authors: George Zhou [University of Southern Queensland], Thomas Soma-Evans [University of Newcastle], Chelsea X. Huang [University of Southern Queensland], Benjamin Pope [University of Queensland], Robert A. Wittenmyer [University of Southern Queensland], Simon J. Murphy [University of Southern Queensland], Duncan Wright [University of Southern Queensland], Jonti Horner [University of Southern Queensland], Belinda Nicholson [University of Southern Queensland] et al.

Abstract: The coming decade will see our Solar System placed into the cosmic context. The diversity in the atmospheres of planets in our Solar System is critical to the differing characteristics of each planet. JWST and other dedicated exoplanet atmospheres missions will unveil the diversity of atmospheres in other planetary systems, allowing us to link composition to processes that govern planet formation and continued evolution. We will also explore the atmospheres of favourable terrestrial planets becoming accessible today, and build techniques, technology demonstrators, and models that will allow us to characterise true Earth analogues in the decades ahead.

Key science questions

- How do the formation and evolution of planets influence their composition?
- How are the atmospheres of planets influenced by their parent stars?
- What is the composition of small planet atmospheres in the habitable zones of other stars?

Key recommendations

- Prioritise retaining membership in ESO, Australia's only major ground-based optical facility capable of exploring exoplanetary atmospheres in 2025-2035. Continued support of domestic high-precision radial velocity facilities to support mass measurements of key targets for JWST, Ariel, and other programs.
- Promote use of flagship international facilities, including JWST, via Australian research grants, including Discovery projects and other PI-led awards.
- Pursue Australian partnership in space-based exoplanet-focused missions at a range of scales, build scientific and industry expertise for future partnerships.
- Promote diversity, equity and inclusion within the Australian exoplanet community

Exoplanet atmospheres will be the window to answer key questions about planet formation, migration, and evolution over the next decade. How do planets form and grow? Did the same processes that shaped today's atmosphere around our Earth also sculpt the thousands of other planets we have now found orbiting other stars? The next ten years present opportunities to understand the composition of planets, from which we can trace their formation histories. The atmospheres of the planets are heavily influenced by their host stars, which drive circulation, non-equilibrium chemistry, magnetic interactions, and erosion; mechanisms that are just beginning to be detectable with current space and ground-based facilities. Technology demonstrators are planned for the next generation of missions that will move us closer to imaging true Earth analogs in the decades after.

Over the last decade, HST and Spitzer observations have revealed clouds and haze in close-in Jovian planets (e.g. Sing et al., 2016), heavy water-rich atmospheres on super-Earths (e.g. Roy et al., 2023), and air-less exteriors for bare-rock ultra-short period terrestrial planets (e.g. Kreidberg et al., 2019). Atomic species have been detected for highly irradiated planets from the ground (e.g. Hoeijmakers et al., 2018, 2019; Yan & Henning, 2018). Helium escape from Jovian and Neptune-sized planets have been detected from HST and ground-based near-infrared facilities (e.g. Allart et al., 2018; Mansfield et al., 2018; Spake et al., 2018), validating the erosion of gas-rich planets over the giga-year timescale (Orell-Miquel et al., 2024). Recent JWST observations revealed definitive signatures of photochemistry in the detection of SO_2 in a number of planets (e.g. Tsai et al., 2023); disequilibrium chemistry caused by tidal heating for close-in Neptune-mass planets (Sing et al., 2024); atmospheres dominated by methane and carbon dioxide for mini-Neptunes in the temperate zone (Benneke et al., 2024; Madhusudhan et al., 2023); and a lack of atmospheres amongst other terrestrial planets (Greene et al., 2023; Zieba et al., 2023).

Australian researchers have led HST programs tracing the atmospheres of super-Earths in the habitable zones of M-dwarfs (Mikal-Evans et al., 2023b), developed one of the first phase-maps of planets with JWST (Mikal-Evans et al., 2023a), and produced high-resolution line lists that enabled the detection of TiO and VO in the atmospheres of irradiated planets (McKemmish et al., 2019, 2016). A particular area of strength in exoplanet science is the Australian leadership in optical interferometry. The only Australian hardware on JWST is its Aperture Masking Interferometer, leading to an Australian partnership in Guaranteed Time Observations on imaging protoplanetary disks at high angular resolution (Tuthill et al., 2022). The nulling interferometer Asgard on VLTI will image young planets and disks previously inaccessible, allowing us to understand the characteristics of planets when they first form (Kraus et al., 2024; Taras et al., 2024). **[Anything else I've missed?]**

How does the formation and evolution of planets influence their composition?

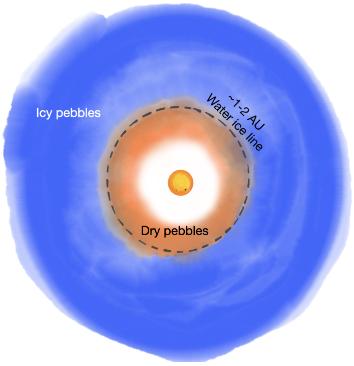

Figure 1: The protoplanetary disk is radially differentiated in its volatile content, and the composition of planets should reflect the composition of the local disk from which they were formed. The inner protoplanetary disk is dry; volatile grains sublimate early on. Beyond the iceline, the disk is cool enough for volatile icy grains to remain solid.

Our current understanding of planet formation and evolution is largely based on the Solar System (Horner et al., 2020). In the Solar System, giant planets like Jupiter and Saturn formed beyond the iceline (Figure 1), i.e. in the outer protoplanetary disk where there is enough material in the gas and ice phase (Pollack et al., 1996). Smaller planets like Earth and Venus formed inside the iceline, with rocky materials that can resist the heat of the early Sun (Raymond et al., 2009). Post formation, the giant planets underwent orbital evolution (migration), resulting in the small size of Mars (Walsh et al., 2011) and unique features in the Kuiper belt (Malhotra, 1995).

Existing JWST programs are already probing the role large scale migration may play on the atmospheres of Neptunes and Jupiters. Observations by Huang et al. (2023) will measure the abundances of the two transiting planets in the TOI-1130 system, with goals including diagnosing the role the outer gas giant played in shaping the composition of the inner sub-Neptune. The BOWIE-ALIGN survey (Kirk et al., 2023, 2024) will probe for composition differences between aligned and misaligned hot Jupiters, with the hypothesis that misaligned gas giants likely originated from volatile rich parts of the outer protoplanet disk.

Over the coming decade, we will have the capability to generalise this model of planet formation and evolution to the thousands of exoplanetary systems discovered around other stars. Do exoplanets form in locations that directly correlate with their bulk properties, similar to the Solar System? What roles do Jupiter-like planets play in other planetary systems? How did their migration affect their atmospheres?

The composition of **smaller planets** should also reflect their mode of formation. Super-Earths or Neptune-sized planets (planets with sizes between 1-4 Earth radius) are found orbiting close-in around 30-50% of Sun-like stars (e.g. Bryson et al., 2021; Burke et al., 2015; Howard et al., 2012; Petigura et al., 2013). Do these planets mirror the ice giants Uranus and Neptune in our own Solar System, or are they a different class of planets unlike any we know well?

Volatile rich sub-Neptunes and super-Earths are being explored by existing JWST programs (e.g. Benneke et al., 2023). Their compositions will be the focus for small planet atmospheres over the next five years. These programs are aimed at understanding the diversity of small volatile-rich planet atmospheres, exploring the role photochemistry, dynamical mixing, and heat redistribution, and cloud regulation climate may play in the atmospheric chemistry. These programs will also hope to constrain planetary formation theories based on measured atmospheric compositions, for example by comparing abundances for key elements such as C, N, O, Fe, Si to deduce formation location and process.

How are the atmospheres and interiors of planets influenced by their parent stars?

Probing atmospheric circulation for highly irradiated gas giants

Most of the short-period (< 5 days) planets observed to date are tidally-locked with the same hemisphere permanently oriented towards the host star, resulting in a highly-asymmetric radiative forcing of the atmosphere. The only effective means of redistributing heat absorbed on the dayside hemisphere to the nightside is through the atmosphere via advective winds. In addition, the chemical composition of the dayside atmosphere will determine the efficiency with which incident starlight is absorbed at different wavelengths, while clouds can simultaneously reflect a significant fraction of starlight before being absorbed into the atmosphere. One of the primary goals of exoplanet science is to understand how radiative transfer, chemistry, and dynamics couple together to maintain a global equilibrium for planetary atmospheres under such a configuration, which in turn will help us to develop increasingly universal models for how planetary atmospheres operate.

The most effective means of characterising the global dynamics and energy budget of short-period planets is with phase-curve measurements, which involved continuously observing a planet over the course of a complete orbit around the host star. In doing so, the emission from both the dayside and nightside planetary hemispheres can be constrained, helping to break the albedo-recirculation degeneracy. The latter arises from the fact that a given level of measured dayside emission can potentially be explained by either a high-albedo planet with inefficient day-night recirculation or a low-albedo planet with an efficient day-night recirculation. By comparing the levels of dayside and nightside emission, the allowed range of albedo-recirculation space is drastically narrowed down. Furthermore, the orbital phase at which the planetary emission peaks encodes information about the atmospheric circulation pattern. If the thermal emission peak is observed either before or after the secondary eclipse, it implies that the hottest region of the dayside hemisphere does not coincide with the substellar point, which in turn indicates the movement of heated gas by winds. Alternatively, if the phase-curve is measured at optical wavelengths, the emission peak may encode information about the distribution of reflective clouds on the dayside hemisphere, which are a crucial component in setting the overall albedo of the atmosphere.

With its incredible pointing and thermal stability, JWST provides an ideal platform for measuring thermal phase curves of exoplanets. One of the first programs to make a phase-curve measurement with JWST is being led by an Australian-based P.I., targeting the high-profile ultrahot Jupiter WASP-121 b (GO-1729, Evans-Soma). At shorter wavelengths, TESS and CHEOPS also provide opportunities to measure phase curves in reflected light, thanks to their high photometric precision and ability to monitor targets continuously for days on end. Australia hosts researchers who have played significant roles in such studies (Daylan et al., 2021; Shporer et al., 2019), including major contributors to the TESS survey in particular (e.g. Huang et al., 2018, 2020).

Towards the first detection of star-planet magnetic interactions

The national involvement in the upcoming Square Kilometre Array, and already its precursor ASKAP, make radio observations of stars and planets an attractive prospect for planetary atmosphere science in Australia. While Jupiter is the brightest object in the solar system at very low ($\sim 10\,\mathrm{MHz}$) radio frequencies, direct emission from solar system objects – let alone exoplanets – is for the time being frustrated by the Earth's ionosphere, which cuts off radio propagation above the frequencies of the signals of interest. Nevertheless, *stellar* radio emission is the best probe of the space weather environment of planets around low-mass stars. In close planetary systems, including the habitable zones of M dwarfs, planets may be inside the 'Alfvén surface' where their magnetospheres do not form a shock protecting them from the stellar wind, but can instead be directly connected to the star – a potentially serious influence on atmospheric mass loss (Garraffo et al., 2017; Kavanagh et al., 2021). This gives rise to bright, circularly-polarized radio emission *around the star* by the electron cyclotron maser instability (Vedantham, 2021; Zarka et al., 2018, 2001), with typical frequencies of order $\sim$ 100s of MHz, in the SKA-Low or LOFAR bands. This has been tentatively detected in several sources using LOFAR (Callingham et al., 2021; Pope et al., 2021; Vedantham et al., 2020), and with an order of magnitude greater sensitivity and precision, SKA-Low is expected to yield many such detections, which are likely to have a fundamental impact on models of space weather and atmospheric loss around M dwarfs, and indeed pave the path to the first detections of exoplanet magnetic fields. Beyond this, radio studies with SKA offer the prospect of detecting coronal mass ejections directly through their associated radio bursts (which otherwise are not constrained by optical flares alone), and characterising in detail the flaring and winds of planet-hosting stars even without star-planet magnetic interaction (e.g. Bloot et al., 2024; Zic et al., 2020). In this context it is vital that the exoplanet atmospheres community and the radio community better engage with one another in planning projects and facilities to better exploit

Australia's uniquely strong position in low-frequency radio science.

Understanding the role atmospheric erosion plays in shaping the small planet population Atmospheric erosion processes dominate the evolution of terrestrial planets in the Solar System. Escaping atmospheres have been observed by spacecraft around Venus (e.g. Bertaux et al., 1978), Earth (e.g. Thomas, 1963), and is the key tracer to understanding water-loss from early Mars (e.g Anderson, 1976; Feldman et al., 2011).

Mass-loss is thought to play an even more dominant role for small planets around other stars. How close-in super-Earths and Neptunes came to be is the major question inspired by the Kepler mission. Fulton et al. (2017) revealed a gap in the radius distribution of small planets, suggesting that atmospheric evaporation, mass-loss, and possible replenishment play key roles in shaping this dominant planet population (e.g. Ginzburg et al., 2018; Kite & Barnett, 2020; Owen & Wu, 2017).

Newly born planets are bombarded by the intense X-ray and UV irradiation from their active host stars, and are losing neutral hydrogen and helium from their atmospheres at a rapid rate. Atomic hydrogen and helium escaping from a young planet can form an envelope up to 50× the size of the planet itself. This envelope absorbs in specific parts of the stellar spectrum, including in the Lyman α line at 120 nm in the extreme UV, and in the helium I triplet at 1038 nm. During transit, the stellar Lyman α emission line can exhibit a $\sim 10\%$ dimming due to the planet's large extended atomic hydrogen atmosphere (e.g. Morrissey et al., 2024; Zhou et al., 2023). Observations such as these are been performed using the Hubble Space Telescope. Similarly, helium escape can be measured via transit observations at the 1083 nm neutral helium line, performed via infrared high resolution spectrographs from large ground-based telescopes.

Large JWST and HST programs have been organised to understand the role evaporation plays in shaping M-dwarf terrestrial planets (Redfield et al., 2024). Over the coming five years, the cosmic shoreline separating terrestrial planets with and without atmospheres – a boundary marked by the XUV irradiation planets receive and their escape velocities (Zahnle & Catling, 2017), will be mapped out empirically. Australian scientists will continue to play a role in mapping the atmospheric mass loss process, with a focus on small planets in their youth to complement these international efforts.

What is the composition of small planet atmospheres in the habitable zones of other stars?

We now have the capability to detect atmospheric features of temperate mini-Neptunes. Temperate mini-Neptunes and super-Earths around M-dwarfs reside close to the ice-line of their respective host stars. The planets may be more water-rich in nature, and are cool enough to have an ocean surface and a hydrogen–helium dominated atmosphere (e.g. Léger et al., 2004; Madhusudhan et al., 2021). HST observations of the temperate super-Earth TOI-270 d (Figure 2, Mikal-Evans et al. 2023b) and K2-18b (Benneke et al., 2019) revealed low molecular weight atmospheres unlike that of terrestrial planets in our Solar System. JWST NIRISS and NIRSpec observations confirmed the presence of water, carbon dioxide, and methane in the atmospheres of these planets (Benneke et al., 2024; Madhusudhan et al., 2023), consistent with both an ocean surface interpretation or a surface-less environment in which water is dissolved in the hydrogen–helium atmosphere.

These super-Earths and mini-Neptunes are the only temperate small planets for which consistent measurements of transmission atmospheric features are now widely accessible. Australian astronomers are actively searching for temperate planets suitable for atmospheric characterisation

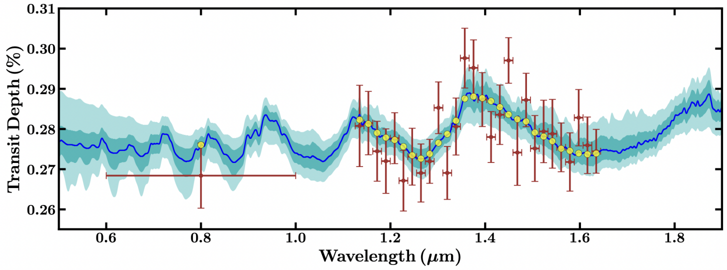

Figure 2: HST WFC3 transmission spectrum of the temperate sub-Neptune TOI-270d showed it likely hosts a low density hydrogen–helium rich atmosphere (Mikal-Evans et al., 2023b).

with JWST (e.g. Dholakia et al., 2024).

Multi-visit campaigns by JWST have the potential to probe for non-equilibrium chemistry and potential bio-signatures in the most favourable terrestrial worlds. Simulations in Mikal-Evans (2022) show that 10-30 JWST transits of TRAPPIST-1e can measure CH_4-CO_2 ratios, if a relatively cloud-free atmosphere exists.

The next decade will see the Australian community helping to lay the ground work for potential JWST successor missions, including Habitable Worlds Observatory, Large Interferometer For Exoplanets (LIFE)[1], and other concepts. Australian scientists may play roles including instrument design (Hansen et al., 2023; Quanz et al., 2022), technology development and prototyping, atmospheric modeling, and long term radial velocity monitoring for target selection.

Summary of facilities and support required

Access to ESO and ELTs, and support for Domestic and International Precise Radial Velocity facilities

ESO is the only major optical observatory directly accessible by Australian scientists. ESO facilities, including VLT-ESPRESSO, Sphere, CRIRES+, VLTI, and HARPS are regularly used by Australian exoplanetary scientists.

Precise radial velocity facilities remain important in the era of JWST, Ariel, and Twinkle. Accurate masses are needed for well-constrained interpretations of atmospheric abundances from JWST. In particular, for small planets with high metallicities, the lack of mass measurements is the limiting factor for the accuracy of atmospheric properties (Batalha et al., 2019).

Australia's domestic precise radial velocity facilities complement ESO access. AAT-**Veloce**, and the **Minerva-Australis** telescope array at Mt Kent Observatory in Queensland, provide long-term monitoring of nearby stars in preparation for Habitable Worlds Observatory. Such monitoring is required to rule out the presence of disruptive giant planets in the habitable zones of the candidate target stars. A Neptune-mass (or larger) planet in the habitable zone will, by its gravitational influence, preclude the presence of Earth-size planets in that region. Hence, long-term monitoring is a critical precursor for optimal target selection for Habitable Worlds Observatory, and hence the overall scope of that mission. Such long-term programs can only be conducted on institution facilities due to the cadence and duration of observations necessary, but are essential to the success of these international flagship missions.

---

[1] `https://life-space-mission.com/`

Support for Guest Investigator programs on flagship missions

The science theme of 'Exoplanets and Exoplanet formation' accounts for 30% of JWST Guest Observer programs. After 'Galaxies and the IGM', the exoplanet community is the largest user of JWST. Australian scientists will continue to lead and participate in Guest Investigator programs on flagship missions to probe the atmospheric composition of planets in the next decade. These programs address fundamental questions: where do planets form, and what influences their atmosphere makeup? Australian investigators are not eligible to benefit from successful NASA Guest Investigator program grants. Domestic support, including ARC Discovery programs, for successful programs that have already received approval from the international community is low risk and high reward.

Australian partnership in space-based observatories

Australian partnerships provide the opportunity for our scientists to participate in their design, planning, and early target selection phases. Australian scientists are already partners of next generation exoplanet missions (e.g. Twinkle). Domestic-led efforts for technology development (Toliman, LIFE technology demonstrator) pave the next step towards detection of true Earth analogues in the 20 year timescale. Specific examples of international mission and mission concepts with significant Australian participation include:

Twinkle The Twinkle Space Telescope (USD$100 million) is a 0.45m telescope to be launched in 2025 to a medium-Earth orbit. Twinkle will perform a transmission and emission spectroscopy survey over its three year primary and three year extended mission, with the goal of understanding the diversity of planet atmospheres (Edwards et al., 2022). Twinkle has the spectral precision to differentiate between Jovian planet atmospheres with differing compositions and origins (Figure 3). Terrestrial planets can be sampled when 20+ transits are obtained (Phillips et al., 2023), within the capabilities of a six-year dedicated exoplanet atmospheres mission.

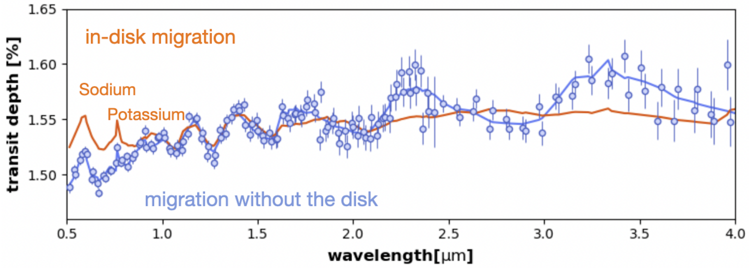

Figure 3: Twinkle observations of Jovian planets can be used to differentiate between different formation processes. We simulate the Twinkle spectra of two planets with similar bulk properties (mass, radius and effective temperature) but different formation pathways. WASP-84 b (red) likely migrated in the protoplanetary disk. HAT-P-17 b (blue) came to its current location through high eccentricity migration after the protoplanetary disk dissipated. Four transits per planet are simulated.

LIFE Technology demonstrator The Large Interferometer For Exoplanets is a mission concept aimed at obtaining thermal emission spectra of temperate terrestrial planets. LIFE is a nulling interferometer that consists of four in-plane collector spacecraft in a rectangular formation, and a fifth out of plane combiner spacecraft. The mission has the potential of detecting bio-signatures, including oxygen, ozone, methane and phosphine, in temperate terrestrial planets. The mission complements monolithic telescope concepts, such as Habitable Worlds Observatory, over wider wavelength ranges. Australian involvement includes interferometer design (Hansen et al., 2023, 2022), and the development of LEO technology demonstrators as precursors for the mission.

Promote diversity, equity and inclusion within the Australian exoplanet community

We look towards necessary improvements in diversity, equity, and inclusion amongst the Australian exoplanet community. JWST user statistics provide one census of the wider exoplanet community. The JWST Cycle 2 Peer Review Results report[2] shows $\sim 14\%$ ($\sim 16\%$) success rate for proposals led by female (male) identified PIs. For context, the fraction of female-PI accepted proposals is 30% for all programs in JWST cycles 1 and 2.

As the topical research direction, exoplanet atmospheres programs can seek to improve the diversity of scientists in the Australian exoplanet community by

- Seeking for at least equal representation amongst HDR students and early career postdoctoral researchers that are funded as a result of successful ARC projects. Seek for more representation amongst co-Is of ARC Discovery project applications.
- Seeking for travel support from AAL, ASA, and other national programs to prioritise underrepresented early career minorities.
- Seeking for the implementation of affirmative action in departmental faculty searches.

References

Allart et al. 2018, Science, 362, 1384
Anderson D. E. 1976, JGR, 81, 1213
Batalha et al. 2019, ApJ, 885, L25
Benneke et al. 2019, ApJ, 887, L14
—. 2023, Exploring the existence and diversity of volatile-rich water worlds, JWST Proposal. Cycle 2, ID. #4098, ,
—. 2024, arXiv e-prints, arXiv:2403.03325
Bertaux et al. 1978, PLANSS, 26, 817
Bloot et al. 2024, A&A, 682, A170
Bryson et al. 2021, AJ, 161, 36
Burke et al. 2015, ApJ, 809, 8
Callingham et al. 2021, Nature Astronomy, 5, 1233
Daylan et al. 2021, AJ, 161, 131
Dholakia et al. 2024, MNRAS, 531, 1276
Edwards et al. 2022, in European Planetary Science Congress, EPSC2022–597
Feldman et al. 2011, ICARUS, 214, 394
Fulton et al. 2017, AJ, 154, 109
Garraffo et al. 2017, ApJ, 843, L33

---

[2] `https://www.stsci.edu/files/live/sites/www/files/home/jwst/science-planning/user-committees/jwst-users-committee/_documents/jwst-cycle2-peer-review-results.pdf`

Ginzburg et al. 2018, MNRAS, 476, 759
Greene et al. 2023, Nature, 618, 39
Hansen et al. 2023, A&A, 670, A57
—. 2022, A&A, 664, A52
Hoeijmakers et al. 2018, Nature, 560, 453
—. 2019, A&A, 627, A165
Horner et al. 2020, PASP, 132, 102001
Howard et al. 2012, ApJS, 201, 15
Huang et al. 2023, The first comparative atmospheric study of a Jovian planet and a sub-Neptune in the TOI-1130 system, JWST Proposal. Cycle 2, ID. #3385, ,
—. 2018, ApJ, 868, L39
—. 2020, Research Notes of the American Astronomical Society, 4, 206
Kavanagh et al. 2021, MNRAS, 504, 1511
Kirk et al. 2023, Does atmospheric composition actually trace formation? Observing aligned vs misaligned hot Jupiters as a testbed, JWST Proposal. Cycle 2, ID. #3838, ,
—. 2024, arXiv e-prints, arXiv:2407.03198
Kite & Barnett. 2020, Proceedings of the National Academy of Science, 117, 18264
Kraus et al. 2024, in EAS2024, 2109
Kreidberg et al. 2019, Nature, 573, 87
Léger et al. 2004, ICARUS, 169, 499
Madhusudhan et al. 2021, ApJ, 918, 1
—. 2023, ApJ, 956, L13
Malhotra. 1995, AJ, 110, 420
Mansfield et al. 2018, ApJ, 868, L34
McKemmish et al. 2019, MNRAS, 488, 2836
—. 2016, MNRAS, 463, 771
Mikal-Evans. 2022, MNRAS, 510, 980
Mikal-Evans et al. 2023a, ApJ, 943, L17
—. 2023b, AJ, 165, 84
Morrissey et al. 2024, arXiv e-prints, arXiv:2408.02170
Orell-Miquel et al. 2024, arXiv e-prints, arXiv:2404.16732
Owen & Wu. 2017, ApJ, 847, 29
Petigura et al. 2013, Proceedings of the National Academy of Science, 110, 19273
Phillips et al. 2023, MNRAS, 526, 2251
Pollack et al. 1996, Icarus, 124, 62
Pope et al. 2021, ApJ, 919, L10
Quanz et al. 2022, A&A, 664, A21
Raymond et al. 2009, Icarus, 203, 644
Redfield et al. 2024, arXiv e-prints, arXiv:2404.02932
Roy et al. 2023, ApJ, 954, L52
Shporer et al. 2019, AJ, 157, 178
Sing et al. 2016, Nature, 529, 59
—. 2024, Nature, 630, 831
Spake et al. 2018, Nature, 557, 68
Taras et al. 2024, Appl. Opt., 63, D41

Thomas. 1963, JGR, 68, 2639
Tsai et al. 2023, Nature, 617, 483
Tuthill et al. 2022, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, 12183Optical and Infrared Interferometry and Imaging VIII, ed. A. Mérand, S. Sallum, & J. Sanchez-Bermudez, 121830Q
Vedantham. 2021, MNRAS, 500, 3898
Vedantham et al. 2020, Nature Astronomy, 4, 577
Walsh et al. 2011, Nature, 475, 206
Yan & Henning. 2018, Nature Astronomy, 2, 714
Zahnle & Catling. 2017, ApJ, 843, 122
Zarka et al. 2018, A&A, 618, A84
—. 2001, Ap&SS, 277, 293
Zhou et al. 2023, Probing active atmospheric erosion across an adolescent planet system, HST Proposal. Cycle 31, ID. #17482, ,
Zic et al. 2020, ApJ, 905, 23
Zieba et al. 2023, Nature, 620, 746